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EXOTIC MULTIQUARK STATES WITH CHARM*

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I. INTRODUCTION

Once upon a time physicists believed that nucleons and pions were elementary like electrons and photons, and that Yukawa's theory of nuclear forces was the analog of QED for strong interactions. Then the Δ was discovered, and then the ρ and other pion resonances, and it became apparent that neither the pion nor the nucleon was elementary and that both had a composite structure. Today pions and nucleons seem to be very similar objects, instead of being very different like the electron and photon, and made of the same basic building blocks: spin 1/2 quarks bound by colored gluons. But perhaps history will repeat itself. Maybe 25 years from now a lecture at Erice will begin with the statement "Once upon a time physicists believed that quarks and gluons were elementary, and that Quantum Chromodynamics (QCD) was the analog

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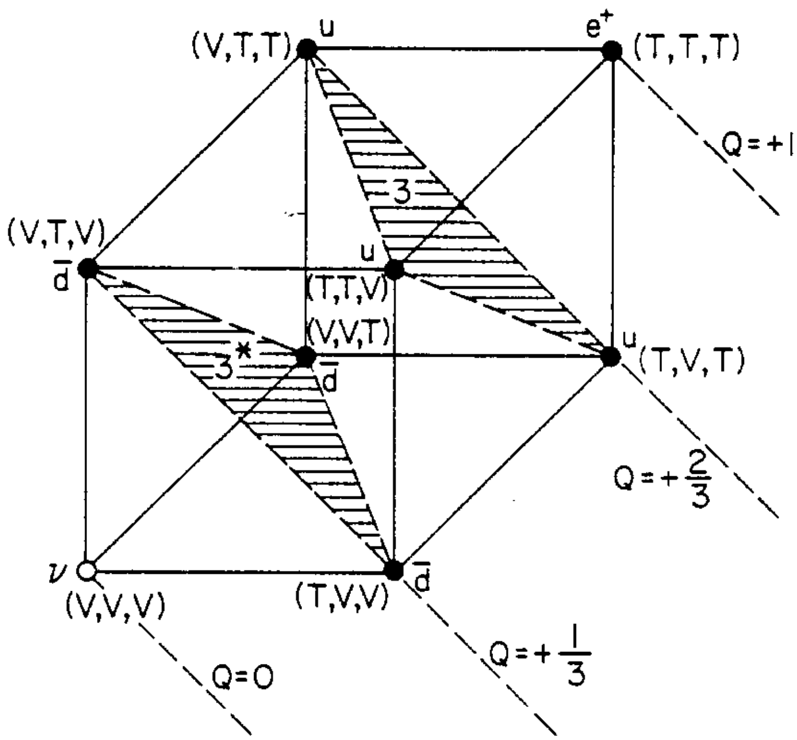
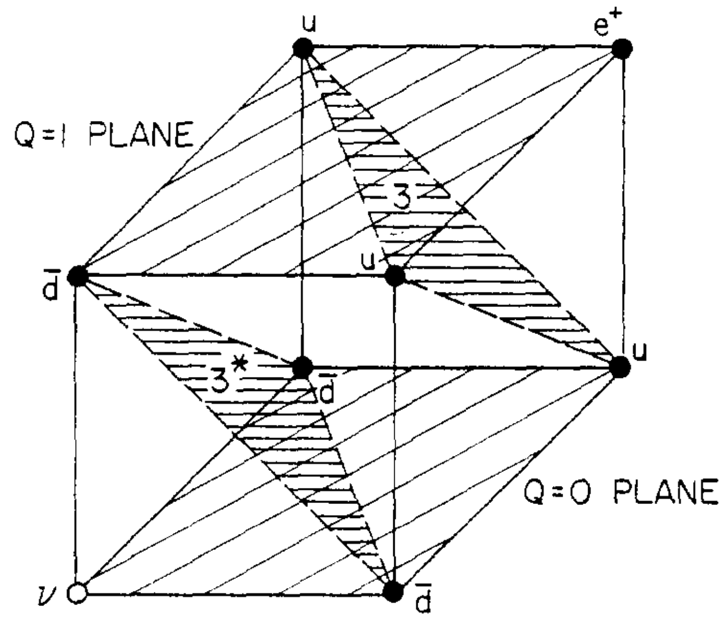
of QED for strong interactions. Then.....????"

Some suggestions already are appearing that quarks and leptons are not elementary but made of more fundamental objects called rishons or preons.[1] The name rishon comes from a Hebrew word which has several interpretations. It is also a short form for the name of a town between Tel Aviv and Rehovot, famous for its winery. A standard excursion for tourists staying in Tel Aviv includes a trip to Rehovot to visit the Weizmann Institute with a stop at Rishon to visit the winery. My friends in public relations at the institute used to complain about the difficulty of explaining anything to these tourists after they had imbibed freely at the winery. So I like to think of rishon physics as the kind of physics done under the influence of Rishon.



The rishon model is described by the cube shown in Fig.1, with the positron, u quark, $\bar{d}$ antiquark and neutrino at the corners. If the cube is taken to be the unit cube, with the neutrino corner at the origin, then the coordinates of each vertex have the form (x,y,z) where x, y and z can be either 0 or 1. If we denote the value 0 by V and the value 1 by T, the coordinates of each vertex are labeled by the constituents of the particle at that vertex in the rishon model. Note that the electric charge axis runs along the diagonal of the cube between the (V,V,V) and (T,T,T) vertices, and that color SU(3) multiplets appear on the planes perpendicular to this diagonal. The values of the electric charge are (0,1/3,2/3,1) for the particles at the vertices of the cube.



Those who prefer integral charges can simply choose a different charge axis to obtain the Han-Nambu cube, shown in Fig.2. Here the charge is the z-axis, and the particles have either charge 0 or +1, with the average charge of each color triplet being the conventional fractional charge of 1/3 or 2/3. Here there are no rishons. It is interesting that the difference between the integrally charged and fractionally charged models has a simple geometrical representation, a rotation of the charge axis in the cube.

One can ask whether the T and V rishons are really fundamental constituents of quarks and leptons, whether they are only labels on a geometrical picture, or whether the true model is really the Han-Nambu cube. But we do not enter into such speculations, and examine the situation as it appears today. We have the new QXD model for everything, where $X = A, B, C, D, E, F, G$, etc. So far there are only models for $X = C, E, F$ and G, but no doubt the others will eventually be discovered as well. However, it is amusing that in the great excitement about non-Abelian gauge theory, the original non-Abelian gauge model for hadron dynamics has faded away. This was the gauge theory of strong interactions mediated by the octet of vector mesons ρ, ω, and K^* coupled to conserved vector currents. The SU(3) group originally introduced by Gell-Mann and Ne'eman is now called flavor and dismissed as an irrelevant complication in the QCD description of strong interactions.

One reason for the success of the quark model was its prediction that the observed hadron states should be those constructed from a quark-antiquark pair and from three quarks. But the question of the possible existence of multiquark states keeps arising and is still open. The whole issue of multiquark spectroscopy has been thoroughly confused by the baryonium fiasco.[2,3] In our considerations, we attempt to avoid these pitfalls.

We begin by noting that there is no bound diproton and no bound dipion.[3] This means that when two protons or two pions are brought together so that the quarks in one hadron are able to feel the short-range forces from the quarks in the other hadron, the resultant forces are insufficient to produce a bound state. But before jumping to the conclusion that there are no bound multiquark states of any kind, let us examine other possible dihadrons carefully.

Is there a bound dikaon? Jaffe[4] contends that the scalar $\delta(980)$ and the $S^*(980)$ are states of two-quarks and two antiquarks, including one strange quark pair. They thus have the constituents of a kaon pair and have a mass just below the mass of two kaons. They might be considered as bound $K\bar{K}$ states. But because the $\delta\pi$ and $\pi\pi$ channels are open at the $K\bar{K}$ threshold, the δ and S^* decay into $\eta\pi$ and $\pi\pi$ respectively, and it is very difficult to establish whether or not they really have the structure of a bound $K\bar{K}$ pair.

But if these scalar mesons are indeed bound $K\bar{K}$ states, the same kind of interactions that bind a K and a $\bar{K}$ can also bind a K with a charmed D meson. If such bound states exist below the DK threshold, they can have peculiar quantum numbers for which no other channels are open for decays by strong interactions. These new possibilities exist for a four-body system when there are four flavors.[5,6] Such exotic mesons with charm and strangeness might be the first exotic states discovered.

There might also be bound states of a baryon B and an anticharmed $\bar{D}$ meson. If these have masses below the BD threshold, they would be "anticharmed baryons" with exotic quantum numbers (the wrong sign of charm for a normal charmed baryon) which could not decay by strong interactions.[3]

Such "threshold exotics" which do not have open channels for strong decays would give unambiguous signatures for a multiquark hadron. It is therefore of interest to look for them experimentally. The possible theoretical basis for their existence has been examined recently[7] as a guide for how and where to look. The basic physics underlying the possible existence of threshold exotics is the observation by Jaffe[4] that although color electric forces saturate and do not lead to binding between color singlet hadrons, color magnetic forces are strong and do not saturate in this way. This has been discussed in detail in my 1977 Erice lectures.[6] A simple way to see this is to note that the N-Δ splitting is much larger than the binding energy of the deuteron. The deuteron binding energy tells us how much binding energy might be gained by ordinary spin-independent forces when two hadrons are brought together. The N-Δ splitting tells us how much energy is available in the spin-dependent interactions. This energy might produce binding of two hadrons brought close together if their spins and color are recoupled from the configuration of two spin-singlet-color-singlet states to the configuration which minimizes the energy. But how can we estimate the binding of such states?

How can we find a good model[3] to estimate the possible binding of multiquark hadrons or threshold exotics? Most physicists today believe that QCD is the correct theory for strong interactions but it still may be wrong. But even if QCD is right nobody knows how to use it to calculate the properties of the observed hadrons. Drastic approximations are needed to get results. Which approximations are good and where do they apply? The models used to get answers all leave out much of the physics. How can we be sure that the physics left out is not important? By investigating where different models work and where they break down perhaps we can learn how to use them with predictive power.

Physics is an experimental science. We discover new things by doing good experiments. Theoretical models help to understand experiments and guide experimentalists to new, fruitful experiments. A <u>good</u> model picks out <u>leading</u> effects, gets agreement with <u>good</u> experimental data, and predicts new phenomena which are <u>found</u> in experiment. A <u>bad</u> model picks out <u>misleading</u> effects, looks for agreement with <u>bad</u> experimental data, and predicts new phenomena which are <u>not</u> found experimentally. The nonrelativistic quark model has been very successful. Many experimental results otherwise not related have been brought together and described by this model[8-15] and many new predictions and suggestions for new experiments have been made. However, the bag models[16] have not yet proved themselves. Bag model calculations generally only reproduce results already known from the nonrelativistic quark model. Their predictions and suggestions for new experiments have not yet been fruitful. And the baryonium bag model has been particularly bad.

Different models are needed to describe hadron structure because nobody knows how to solve the relativistic many-body problem remaining even after the glue and the ocean of pairs are neglected. Simplified models are invented which can be solved, each at the price of omitting some of the physics. Each is useful for different types of data; namely those where the physics omitted is not important. The M.I.T. bag model[16] reduces the relativistic n-body problem to a relativistic one-body problem. It is useful for testing relativistic effects, but neglects two-body correlations of the type successfully demonstrated in the calculation of the neutron charge radius and in the Isgur-Karl[17] treatment of strange baryons with unequal mass quarks. The harmonic oscillator shell model is nonrelativistic, but furnishes a shell model which can be solved exactly and which includes two-body correlations. It is the only model in which the center-of-mass motion is treated exactly and spurious excitations are simply separated. Another potential model which has been used is the Quigg-Rosner logarithmic potential.[18] Although this potential is not tractable for the three-body problem, many results are obtained without full calculations using the scaling properties of the potential; in particular results relating meson and baryon spectra.

To investigate multiquark systems, we need a model that works for two and three-body systems and is easily extended to treat more particles. The bag model has too much freedom and not enough experimental constraints. It can be made to fit almost anything and has little predictive power. It is particularly unreliable for multiquark systems because the confinement is put in by hand for each n body system, and there is no simple unambiguous prescription for how confinement varies with n. When the bag model Hamiltonian is defined for the quark-antiquark meson system, there is no unambigous prediction for extension to the n quark system and no prediction that the diproton is unbound.

The quasinuclear colored quark model in which quarks and antiquarks interact with a universal two-body color exchange force[8,9] has proved to be very successful in treating mesons and baryons and has very few free parameters. All the parameters for the n-body system can be determined in the meson sector with no further freedom. Its success in treating baryons and its natural explanation for the absence of bound diprotons and bound dipions suggests its use for treating threshold exotics.

We justify the use of a nonrelativistic quark model as an expansion in a "small" parameter, v/c, which is manifestly not small. In the old days, when we learned quantum electrodynamics from Heitler's book, we calculated results to lowest order in perturbation theory and found good agreement with experiment, even though perturbation theory was obviously no good and higher order corrections were infinite. But the parameters used in the perturbation theory were not fundamental parameters in a theory from first principles. They were phenomenological parameters fitted to the experimental values of the charge and mass of the electron. Subsequent developments in renormalization showed that the use of these phenomenological parameters, rather than bare parameters, automatically included infinite sums of higher order terms. We therefore assume that something similar may eventually justify the simple nonrelativistic quark model which also uses phenomenological parameters. There may be something in it which we do not yet understand. Perhaps some hidden principle of relativistic regularization, asymptotic relativistic freedom, etc. will eventually be derived and explain why the model works. Meawhile we use the same approach of all unjustified perturbation expansions. Calculate the first non-trivial term, throw the rest away without looking at it and compare with experiment.

For our treatment of multiquark systems we use a naive quark model[8,9] which has had surprising success. It gives a universal mass formula for the mass M_h of any hadron in terms of the masses of the constituent quarks m_i and a hyperfine interaction depending on their spins $\vec{\sigma}_i$

$$M_h = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j} \langle v_{ij} \rangle \tag{1}$$

where $\langle v_{ij} \rangle$ is the value of the matrix element of the hyperfine interaction. This formula immediately gives the successful relation between meson and baryon masses[8,14]

$$\begin{aligned} M_\Lambda - M_N = 177 \text{ MeV} &= m_s - m_u \\ &= (3/4)(M_{K^*} - M_\rho) + (1/4)(M_K - M_\pi) = 180 \text{ MeV} \end{aligned} \tag{2}$$

The additional assumption that the magnetic moment μ_i of a quark with electric charge e_i is given by

$$\mu_i = e_i (M_p / m_i) \qquad \text{nuclear magnetons} \tag{3}$$

together with the standard SU(6) baryon wave functions gives two relations[3,4] for the magnetic moment of the Λ,

$$\mu_\Lambda = -0.61 \text{ n.m.} = (-1/3)\left[(1/\mu_p) + (M_\Lambda - M_p)/M_p\right]^{-1} = -0.61 \text{ n.m.} \tag{4a}$$

$$\begin{aligned} \mu_\Lambda = -0.61 \text{ n.m.} &= -(\mu_p/3)\left(\frac{m_u}{m_s}\right) \\ &= -(\mu_p/3)(M_{\Sigma^{*+}} - M_{\Sigma^+})/(M_{\Delta^+} - M_p) = -0.61 \text{ n.m.} \end{aligned} \tag{4b}$$

This remarkable agreement is very surprising in view of known neglected effects considerably larger than the difference between the theoretical and experimental values. It can be understood only if these neglected effects conspire to give contributions absorbed in the definition of the quark mass parameters m_i which are not determined by first principles but by fitting data. These quark mass parameters appear in both terms in Eq.(1) and in Eq.(3); i.e. as direct contributions to hadron masses, as coefficients in the strong hyperfine interaction responsible for spin splittings, and in the magnetic moments. The success of Eqs.(2) and (4) imply that the corrections to m_i in all three places in Eqs.(2) and (3) for baryons and in the first term of Eq.(1) for mesons are nearly the same. Note that Eqs.(2) and (4a) do not involve the second term in Eq.(1) nor Eq.(3) for mesons.

The zero point kinetic and potential energies and relativistic effects neglected in Eqs.(1) and (3) have been investigated and shown to fit into the general pattern discussed above. Although they are large, their main contribution can be absorbed by changing the values of the mass parameter m_i in nearly the same way for mesons and baryons in the first term of Eq.(1) and in the magnetic moment (3). These effects produce a small difference in m_i between mesons and baryons which does not affect the relation (2) because m_s and m_u are shifted by about the same amount. It does not affect Eqs.(4a) and (4b) which involve only baryons. But this difference is observable in other experimental quantities calculated explicitly to give new relations which agree with experiment.[12]

The zero point energy in meson and baryon systems was calculated [12] in the quasinuclear model of Refs.(8,9) as the ground state expectation value of the Hamiltonian for a system of n particles interacting with a two-body color exchange logarithmic potential

$$E_0 = \langle H\rangle = \sum_i m_i + \sum_i \frac{p_i^2}{2m_i} + \sum_{i>j} Uk_{ij}\log(r_{ij}/r_0) \qquad (5)$$

where $U = 733$ MeV is the strength of the Quigg-Rosner logarithmic potential[18,19] and k_{ij} is a color factor. The rest mass contribution to the energy is included, but the non-relativistic expression for the kinetic energy is used. The spin-dependent contribution is averaged out to give the zero point energy for the appropriate spin averages of the hadron masses used in Eq.(2). Evaluating the color factors and using the virial theorem gives a result valid for any n-body color-singlet bound state of quarks and antiquarks[8,9] with complete symmetry between the n constituents.

$$E_0(n) = n\left[m + \frac{U}{4} + \frac{U}{2}\langle\log(r/r_0)\rangle_n\right] \equiv n\, m_{eff} \qquad (6)$$

where m_{eff} is defined as the effective quark mass.

To the extent that the variation in $\langle\log r\rangle$ from one hadron to another can be neglected, the zero point energy and the hadron masses are proportional to n, giving the familiar "quark counting" 3/2 ratio for baryon to meson masses and the same value of m_{eff} for both systems. The correction to this value of 3/2 and the difference in m_{eff} are determined from the difference in $\langle\log(r)\rangle$ between mesons and baryons,

$$\left[m_{eff}(\mathrm{bar}) - m_{eff}(\mathrm{mes})\right]_{theo} = \frac{U}{2}\log\,(2/\sqrt{3}) = 53 \text{ MeV} \qquad (7a)$$

where the value $2/\sqrt{3}$ comes from the assumption that r scales like $(p^2)^{-1/2}$ between mesons and baryons and using the scaling factor for p^2 from the virial theorem in Refs.(8,9). This can be compared with experimental values of spin averaged meson and baryon masses.

$$[m_{eff}(\text{bar}) - m_{eff}(\text{mes})]_{exp} = \frac{M(N) + M(\Delta)}{6} - \frac{3M(\rho) + M(\pi)}{8} \tag{7b}$$
$$= 54.5 \pm 1.5 \text{ MeV}$$

The change in effective quark mass (7) between mesons and baryons is independent of quark flavor and cancels in any flavor-dependence relation analogous to (2).

In view of the success of this model for the $n = 2$ and $n = 3$ systems, we apply it also to the case of $n = 4$. Equation (6) shows that when the spin effects are averaged out the energy of the ground state of the n-body system is proportional to n. This means that the four-body system has exactly the same energy as two two-body systems and will be unbound and unstable against breakup into two two-body mesons. However, the spin dependent part of the two-body interaction given by the second term of Eq.(1) can produce binding. This describes formally the qualitative argument given above and originally due to Jaffe. We now examine the effects of this hyperfine interaction in the four-body system in a quantitative way following Ref.7.

The four quark scalar states can be considered as bound states of two ordinary pseudoscalar mesons, with binding provided by the hyperfine interaction. The basic physics can be seen as follows: Consider a state of two pseudoscalar mesons placed very close together to form a four-particle $qq\bar{q}\bar{q}$ cluster. In the original color-spin coupling each meson is a quark-antiquark pair in a spin-singlet-color-singlet state and there is no force between the quarks in one meson and the quarks in the other. But suppose the colors and spins of the four particles are recoupled to introduce color octet and spin triplet components into each pair while keeping the overall four-particle state a color singlet and spin singlet. The color-electric interaction is not changed by this recoupling, as is seen from Eq.(6), since it is the same for any spatially symmetric color singlet state. But the spin-dependent hyperfine interaction can change. Some energy is lost in the hyperfine energy of each original pair since the state which is the singlet in both color and spin has the lowest energy. But there are four new pairs involving a quark or antiquark in one of the old pairs and a quark or antiquark in the other. Before the recoupling there was no interaction energy in these four pairs. Binding can occur if recoupling gains more binding energy in the forces between the four new pairs than it loses in the forces between the two old pairs.

To determine whether a four particle bound state exists the possible gain in potential energy due to color and spin recoupling must be balanced against the increase in kinetic energy required to keep the four-body system together rather than allowing it to separate into two mesons. The gain in potential energy can easily be calculated, using Jaffe's color-spin force and experimental values for observed hyperfine splittings, for a four-particle wave function which has a spatial dependence between each pair which is the same as any other pair (e.g., like the four nucleons in an alpha particle) and is the same as in ordinary quark-antiquark mesons where the values of the hyperfine interaction matrix elements are known from experimental hyperfine splittings. In the cases of interest, an appreciable gain in potential energy is obtained by such a recoupling of spins, as is shown below. However, it is not clear if this is sufficient to overcome the effect of the kinetic energy. The question of how to modify the wave function from this simple α-particle structure in a way which minimizes the energy has no simple model-independent answer, since it depends upon how the color charge and color hyperfine interactions change when the four-particle wave function is scaled up in size or takes on a two-center molecular type configuration rather than that of an alpha particle. Such asymmetric wavefunctions can also lead to effects from color electricity as well as from the confinement potential if this latter is color dependent.[20,21]

The existence of the δ and S^* just below the $K\bar{K}$ threshold indicates that such binding occurs for the four-quark system. Jaffe has pointed out that the degeneracy of the isovector δ and the isoscalar S^* which couples much more strongly to $K\bar{K}$ than to $\pi\pi$ is simply explained in the four quark model and not in the standard $q\bar{q}$ model and that the masses are in the right ball park. We note that the description of these states as just barely bound states of the $K\bar{K}$ system provides a natural explanation for the occurence of these states right at the $K\bar{K}$ threshold. There is no simple explanation for this striking experimental fact if the δ and S^* are ordinary $q\bar{q}$ mesons.

We therefore suggest that similar bound states of $D\bar{K}$ and DK should exist near and possibly below the DK threshold. The isoscalar states of these two configurations,[5,6] denoted by $\tilde{F}_s$ and F_x would then be stable against strong decay.

The increase in potential energy from color-spin recoupling can be calculated for the alpha particle configuration using Jaffe's expressions for the hyperfine interaction.[4] We consider the four-quark SU(6) scalar state with the color-spin classification (21,21*) in the SU(6) x SU(6) classification, where the two SU(6) groups are the color-spin groups for the quarks and antiquarks respectively. (For illustrative purposes the effect of [1] - [405] SU(6) color-spin mixing is neglected and the result of the exact calculation is quoted below[22].) The expectation values of the hyperfine interaction in this wave function for a quark antiquark pair and a quark-quark pair respectively are found to be

$$M_{q\bar{q}}(21,21^*) = -(3/7)(M_V - M_P) \tag{8a}$$

$$M_{qq}(21,21^*) = M_{\bar{q}\bar{q}}(21,21^*) = -(3/28)\ (M_V - M_P) \tag{8b}$$

where $M_V - M_P$ is the hyperfine splitting for the conventional $q\bar{q}$ mesons, given by the experimental value of the mass difference between the vector and pseudoscalar mesons. The hyperfine interaction in a conventional pseudoscalar meson is just

$$M_{q\bar{q}}(P) = -(3/4)(M_V - M_P) \tag{9a}$$

This is greater than the value of the hyperfine interaction (8a) for a quark-antiquark pair in the (21,21*) state, as expected. The change in energy of a $q\bar{q}$ pair in recoupling its spin from the pseudoscalar color-singlet-spin-singlet state to the (21,21*) state is given by the difference between (8a) and (9a)

$$M_{q\bar{q}}(21,21^*) - M_{q\bar{q}}(P) = (9/28)(M_V - M_P) \tag{9b}$$

The change in binding energy of the alpha particle configuration in recoupling the colors and spins from the two pseudoscalar configuration to the (21,21*) configuration is seen to contain three components. Equation (9b) gives the loss in binding energy for each of the two $q\bar{q}$ pairs that were originally coupled to pseudoscalar mesons. Eq.(8a) gives the gain in binding energy for each of the two $q\bar{q}$ pairs which were intially not in the same meson and had no initial hyperfine interaction. Eq.(8b) gives the gain in the binding energy for qq and $\bar{q}\bar{q}$ pairs which also had no initial hyperfine interaction. The net gain in binding for the alpha particle configuration over the 2P configuration is then given by

$$M(\alpha) - 2M(P) = -2\left(\frac{3}{7} + \frac{3}{28} - \frac{9}{28}\right)(M_V - M_P) = -\frac{3}{7}(M_V - M_P) \tag{10}$$

The exact calculation gives $-0.53(M_V - M_P)$, about 25% larger.

Since vector-pseudoscalar splittings are typically several hundreds of MeV, the gain in potential energy from color-spin recoupling in the alpha particle configuration is also several hundreds of MeV. This is sufficient to be taken seriously as a source for binding. However, the zero point kinetic energies per degree of freedom are of the same order of magnitude. As mentioned above, whether the binding is sufficient is a dynamical question requiring detailed study[21]; for now, we assume from the $K\bar{K}$ system that binding does indeed occur. (Note, for example, that the usual δ-function potential used for the hyperfine interaction is valid only in perturbation theory, and that it is too singular to give a sensible result in the Schrödinger equation.)

The expression (10) assumes SU(4) flavor symmetry in which the hyperfine interaction is flavor-independent. However, flavor dependence is easily included if we keep the (21,21*) wave function. This gives an upper bound on the hyperfine energy, since it will be possible to lower the energy by slight changes in color-spin recoupling from the symmetric (21,21*) configuration if the hyperfine couplings of the quarks are different. For this purpose the expressions (8) and (9b) are convenient since each can have a different flavor dependence.

Consider the $D\bar{K}$ and DK systems which might bind to produce the $\tilde{F}_s$ and F_x states respectively. These contain six pairs with flavors (cs),(cu), (cd), (su), (sd) and (ud). Each pair gives a contribution to the binding which has the form (8a),(8b) or (9b) depending upon whether it is a quark-antiquark or quark-quark pair not in the original mesons or whether it is a pair which was in an original meson state. For each pair the relevant value of $M_V - M_P$ is the hyperfine splitting corresponding to the flavors of the particular pair. We thus obtain

$$\begin{aligned} M\{\alpha;F_x(cu\bar{s}\bar{u})\} - M(D) - M(K) &= -(3/7)(M_\rho - M_\pi + M_{F^*} - M_F) \\ &\quad + (3/14)(M_{K^*} - M_K + M_{D^*} - M_D) \qquad (11a) \\ &= 205 \text{ MeV} \quad . \end{aligned}$$

$$M\{\alpha;\tilde{F}_s(cs\bar{u}\bar{d})\} - M(D) - M(K) = -(3/28)(M_\rho - M_\pi + M_{F*} - M_F + M_{K*} - M_K + M_{D*} - M_D) = 140 \text{ MeV} \tag{11b}$$

where $M\{\alpha;\ldots\}$ denotes the potential energy in the alpha particle configuration for the quantum numbers indicated (recall we have isovector-isoscalar degeneracy).

For the case of the $K\bar{K}$ system which can bind to produce the δ and S^* states, expressions entirely in terms of experimental hyperfine splittings like (11) cannot be obtained, since the hyperfine splitting for an $(s\bar{s})$ pair is obscured by mixing and not directly available from experiment. If we assume that hyperfine splittings are inversely proportional to quark masses, we obtain the result

$$M(\alpha,\delta) - 2M(K) = -(3/7)(M_{K*} - M_K)\{1 + (\frac{m_s}{m_u} + \frac{m_u}{m_s} - 2)\} \simeq -200 \text{ MeV} \tag{12}$$

where m_s and m_u are the masses of the strange and up quarks and we have set $m_u/m_s = 2/3$ to obtain the numerical result. Note that this result is very insensitive to the value of m_u/m_s.

These energies are all in the right ball park to suggest that spatial configurations exist in which these potential energies can barely win over the kinetic energies to produce a bound state. One would expect kinetic energy effects to be smaller for the charmed system because of the increased mass; thus if the S^* and δ are bound $K\bar{K}$ states, the F_x should also be bound and the $\tilde{F}_s$ borderline. The same argument applied to the $\pi\pi$ and $K\pi$ systems could explain the absence of bound ε and κ states.

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22. This calculation may be made using Jaffe's result for [1] - [405] mixing in references (4) if one takes into account that in equation (3.19) of the second article the sign of the $|0^+ \underline{9}\ [405]\rangle$ state should be reversed.